Bioenergy and Food Security
Modeling Income Effects in a Partial Equilibrium Model

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Abstract— **Bioenergy has been politically promoted as a means to mitigate air pollution, climate change, and scarcity of fossil energy sources. This study addresses the question whether increased agricultural incomes from bioenergy production will improve food security despite increasing food prices. We use a small partial equilibrium to analyze bioenergy policies. Through an iterative procedure, income changes are used to shift food demand curves until equilibrium. Our results show that despite global reductions in food production, undernourishment may decrease in certain locations, where bioenergy production occurs.**

Keywords— **Food security, Bioenergy policy, Income changes, Partial equilibrium model.**

I. INTRODUCTION

Bioenergy has been politically promoted as a means to mitigate air pollution, climate change, and scarcity of fossil energy sources. Uncertainty and controversy exists about the environmental and societal side effects of bioenergy. Possible negative environmental impacts include increased nitrous oxide emissions [1] and consequences of emission leakage through agricultural intensification and expansion into native forests [2]. Society as a whole may suffer from increased food prices [3]. However, bioenergy production may generate additional income and employment opportunities in the agricultural sector [4]. Land rents and wage rates are likely to increase. In short, to assure efficiency of bioenergy policies, comprehensive scientific assessments are needed.

Assessments of the complex impacts of bioenergy policies face several challenges. First, competition for scarce land may cause substantial feedbacks from the bioenergy sector to the food, fiber, timber, and nature reserve sectors. Second, international trade of agricultural and forest commodities may leak regional policy impacts to other countries. The leakage effects may assume non-linear proportions [5,6]. Third, agricultural resources are very heterogeneous with respect to natural and technological conditions. Fourth, land use choices simultaneously affect soil and water properties, climate, and biodiversity. Benefits in one environmental category may be compromised by damages in another [7].

Previous bioenergy studies have managed the described four challenges in different ways. Geographic, engineering, and microeconomic studies focus on the variation in technological and natural conditions [8-10]. International trade, market, income, and leakage effects are typically ignored. Land competition is also ignored or exogenously treated. Environmental impacts are omitted or limited to greenhouse gas balances. Macroeconomic bioenergy studies can be grouped in two basic approaches. Top-down, computable general equilibrium (CGE) models are well-suited to analyze market feedbacks, international trade, emission leakage, and income effects [11-13]. Thus, these models can assess the impacts of bioenergy on poverty and malnutrition. However, the representation of natural and technological variation is very coarse and often abstract. In turn, the lack of technological details prevents a good representation of complex environmental impacts.

The second type of macroeconomic studies uses bottom-up, partial equilibrium models [3,14-16]. Advantages of this design include a more detailed representation of natural and technological variation, multiple environmental accounts also portraying emission leakage, and endogenous depiction of international agricultural markets. The weakness of partial equilibrium models lies in their omission of adjustments in excluded sectors and in their omission of income effects. Because food security relates more to purchasing power than to physical availability of food, partial equilibrium models seem inadequate to analyze the impact of bioenergy policies on hunger and malnutrition.

The above arguments imply that none of the existing approaches can fully capture the complex environmental and societal impacts of bioenergy policies. Several potential remedies are conceivable. First, partial and general equilibrium models could be linked. Such links have been established in the past for certain research questions [17]. Second, CGE models could be resolved further to more adequately capture natural and technological heterogeneities. Comparison of CGE studies from different times shows that this is indeed happening, however, the refinement speed is limited by computational and data resources. Third, partial equilibrium models could be expanded to cover excluded sectors and to represent income effects. Essentially, this would imply to convert partial into general equilibrium models. Again, computational and data restrictions limit the applicability of this strategy. In this paper, we use a computationally feasible variant of the third approach. Particularly, we show how small modifications of a partial equilibrium structure can be used to include some of the policy induced income changes.

II. METHODOLOGY

To examine the impact of bioenergy development on income and food security, we develop a small illustrative partial equilibrium model of the global agricultural sector. There are three reasons for adopting a small model. First, our focus is on the methodology rather than on exact empirical estimates. Small models give a clearer understanding of individual processes because the dampening or enhancing influence of other processes is limited. Second, small models save time and computing resources. Nevertheless, the structure of our small model can easily be imposed on large models. In fact, experimental implementations of this method in a global forest and agricultural sector optimization model proved straightforward. Third, small model results can easily be reproduced.

Our illustrative partial equilibrium model consists of three regions (index r) – Europe (EU), Sub-Saharan Africa (SSA), and the rest of the world (RoW). Agricultural production involves two aggregated commodities - food and bioenergy (index z). There is only one explicit resource – land (index x). Other factors, i.e. labor, water, energy, and capital, are embedded in the production cost parameter. The model consists of 3 main equation blocks: an objective function (Equation 1), commodity balance equations for food and bioenergy in all three regions (Equation 2), and balance equations for the agricultural resource in each region (Equation 3). Food demand is separated into demand within the agricultural sector and demand from all other sectors. The objective function maximizes the areas underneath the food demand curves minus the areas underneath the resource supply curves minus the sum of all production and trade costs. For the assumed competitive markets, such an objective specification is equivalent to maximizing the sum of consumer surplus from food markets plus the sum of producer surplus from resource markets.

$$\begin{aligned} Max \quad \Pi = & \sum_{r,z} \int D_{r,z}\left(q_{r,z}\right) dq_{r,z} \\ & - \sum_{r,x} \int S_{r,x}\left(q_{r,x}\right) dq_{r,x} \\ & - \sum_{r,y} c_{r,y} \cdot q_{r,y} \\ & - \sum_{r,\tilde{r},y} t_{r,\tilde{r},y} \cdot s_{r,\tilde{r},y} \end{aligned} \tag{1}$$

$$\begin{aligned} & q_{r,z} + \sum_{r,z} s_{r,\tilde{r},z} \\ & - \sum_{y} a_{r,y,z} \cdot q_{r,y} - \sum_{\tilde{r},z} s_{\tilde{r},r,z} \le 0 \end{aligned} \tag{2}$$

$$w_{r,x} - \sum_{y} a_{r,y,x} \cdot q_{r,y} \le 0 \tag{3}$$

Agricultural resource usage is constrained through an upward sloping supply function. Food sales face a downward sloping demand function. Both food demand and resource supply function are specified as constant elasticity functions. The resulting nonlinear objective function terms are stepwise linearly approximated[1]. Bioenergy demand is imposed as an exogenous restriction. Interregional trade is allowed

[1] The linear approximation results in two additional constraints. Details are available from the authors.

for both commodities but subject to transportation and trade policy costs. All exogenous parameters are displayed in Table 1. Production costs for food are calibrated to equate marginal revenues with marginal costs at observed food production levels. The trading costs for food are adjusted so that the base model solution is close to observed trade flows. These trade flows are derived from public statistics of the Food and Agricultural Organization.

Table 1 Exogenous model parameters

Parameter	Unit	EU	SSA	RoW
Food yield	1E6 kcal/ha	13	4	9
Bioenergy yield	GJ/ha	18	13	45
Bioenergy production cost	$/ha	792	350	675
EU Food export costs	$/cu		40	12
SSA Food export costs	$/cu	250		50
RoW Food export costs	$/cu	107	56	
Land supply price elasticity		0.3	0.3	0.3
Food demand price elasticity		-0.3	-0.7	-0.6
Food consumption (all sectors)	1E12 kcal	770	570	5410
Food price	$/1E6 kcal	224	173	117
Income elasticity of food demand		0.3	0.7	0.6

A. Income Changes of Bioenergy Policies

A major aspect of this study is to examine if a partial equilibrium model of the agricultural sector can meaningfully portray hypothesized positive income effects of bioenergy policies on food security. Let us first discuss the qualitative impacts of a bioenergy policy. In absence of environmental feedbacks, the total sum of market welfare across consumers and producers in all three regions would decrease by an amount that is referred to by economists as dead weight loss. Essentially, the government would force the production and use of bioenergy instead of cheaper energy alternatives on the market. Society then incurs the increased cost of bioenergy as an overall loss. However, if the bioenergy target is an efficient mean of reducing the damage from climate change, the dead weight loss would be somewhat compensated by benefits from reduced environmental externalities. Without such benefits, a bioenergy policy can only increase food security if the impact of a change in income distribution is higher than the overall income loss. Bioenergy policies cause more financial transactions in the agricultural sector but fewer transactions in the fossil energy sector. Energy becomes more expensive in all sectors. Thus, the income effects differ between the non-agricultural and agricultural sectors. Additional differences may arise across countries. Nations with relatively low bioenergy production costs may gain relative to others. Fossil energy producing nations may incur most losses.

The arguments above imply that an analysis of the income effects from a bioenergy policy is only meaningful if the change in income distribution is represented, preferably between countries but also between agricultural and non-agricultural sectors.

In partial equilibrium, agricultural sector models, several income related measures exist: profits, revenues, producer surplus, and consumer surplus. Which one of these measures is appropriate to approximate changes in purchasing power by agricultural bioenergy producers? First, classical economic theory states that competitive markets yield zero profits, where total revenue equals total expenditure. In a partial equilibrium model, this condition always holds regardless of the magnitude and direction of technological, political, or environmental changes. Therefore, profits are not a suitable candidate for income effects in these models.

Second, while total profits always remain zero, the volume of financial transactions, i.e. total product revenues may expand or contract. The change in total national revenues appears suitable as proxy for the change in national income. Note that gross domestic product (GDP) is defined as the total market value for all final goods and services produced within a country in a given period of time. However, one should bear in mind that such measures are an incomplete proxy for international income distribution effects because changes in other sectors would not be considered. The third and fourth income items involve changes in consumer and producer surplus. Producer surplus is a rent on scare resources and defined as producer revenue minus production costs. Changes in agricultural labour surplus measure the net income change for agricultural workers. Similarly, changes in land surplus identify the change in land rents or net income changes for land owners. Consumer surplus changes represent net income changes for consumers of food and essentially involve the total population including farmers[2].

In light of the above arguments, we use producer surplus changes to approximate regional income changes ($\Delta\eta_r$, Equation 4).

$$\Delta\eta_r = \sum_x \left(\begin{array}{l} S_{r,x}\left(q^{*1}_{r,x}\right)\cdot q^{*1}_{r,x} - \int_0^{q^{*1}_{r,x}} S_{r,x}\left(q_{r,x}\right)dq_{r,x} \\ -S_{r,x}\left(q^{*0}_{r,x}\right)\cdot q^{*0}_{r,x} + \int_0^{q^{*0}_{r,x}} S_{r,x}\left(q_{r,x}\right)dq_{r,x} \end{array} \right) \quad (4)$$

B. Demand Shifts

Commodity demand functions in partial equilibrium models depict the own price response of demand holding all other commodity prices and income constant. Here, we use constant elasticity functions. To uniquely identify such a function, three exogenous parameters are sufficient. These include an elasticity value and a price-quantity pair through which the function passes. Such a pair can be conveniently obtained by taking observed price and demand levels. For our small illustrative model, we formed a consumption weighted average of food price and quantity over all major food commodities also accounting for different caloric values of these products. Based on population ratios, we decomposed food quantities into agricultural and non-agricultural consumption.

If income levels change, commodity demand functions will shift (Equation 5). We use income and commodity sensitive elasticities from [18] and apply these elasticities on the relative income change derived from the absolute income change in Equation 4. As shown, we also account for the share of agricultural GDP relative to total GDP. After each demand shift, the model is solved again, income changes are recomputed, and demand curves shifted again. This iterative procedure continues until equilibrium, i.e. until the demand shifts become so small that the resulting income impacts are below a small threshold. Our experiments showed fast convergence usually within 10 iterations.

$$\hat{q}^1_{r,z} = \hat{q}^0_{r,z}\cdot\left(1+\varepsilon_z\cdot\vartheta^{GDP}_r\cdot\frac{\Delta\eta_r}{\eta^0_r}\right) \quad (5)$$

C. Prevalence of Undernourishment

The prevalence of undernourishment identifies the part of the population whose food consumption falls below the minimum requirement. We use a method developed by the Food and Agricultural Organization. This method was mandated in 1996 by the World Food Summit to monitor the progress towards the objective of halving the number of hungry people by 2015. The measure is based on the comparison of the actual food consumption expressed in terms of dietary energy with a minimum energy. The distribution of dietary energy consumption across a country's population is assumed to be log-normal described by the mean value and the coefficient of variation. To estimate the coefficient of variation two sources of variation are considered: the per capita income and the minimum energy requirements. While the minimum requirement component is assumed fixed at 0.2, the per capita income component is estimated based on household income/expenditure surveys. The overall daily minimum energy requirement, which is used as cut-off point, is an aggregation of gender and age specific requirements weighted by the proportion of each cohort within the total population.

III. EMPIRICAL RESULTS

To estimate food security implications of bioenergy promotion, we combine three regional policy implementation assumptions (EU only for scenario 1, SSA only for scenario 2, and RoW only for scenario 3) with 12 bioenergy target levels. Figure 1 shows food prices change in all three regions under a bioenergy

[2] This holds especially for an industrialized agriculture but less for subsistence agriculture.

policy in Sub-Saharan Africa. We observe that the income effect leads to higher food prices and that the bioenergy policy impacts are transmitted through international trade to other regions. In fact, the highest food price increase is not observed in SSA but in RoW. Figure 2 shows that the integration of income effects substantially increases global agricultural land use. This additional land requirement is an important driver for the overall environmental balance of bioenergy.

In Figure 3, we illustrate the quantitative impacts on food security in SSA. We find a substantial reduction in undernourishment only for high bioenergy targets in SSA. European or RoW targets reduce undernourishment result in much less reduction. Figure 4 shows the level and change in marginal bioenergy costs. For an EU bioenergy policy we find a strong increase after a target level of 1000 GJ. The other scenarios do not yield strong changes.

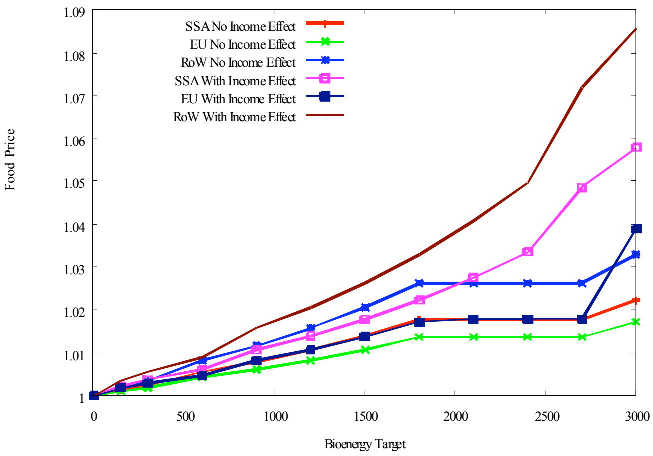

Figure 1 Food price

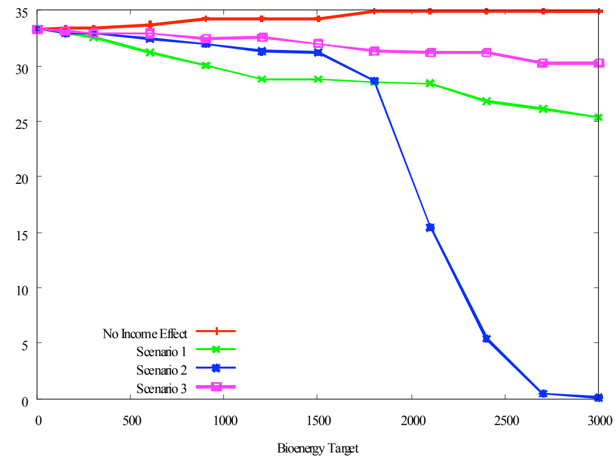

Figure 3 Prevalence of undernourishment in SSA

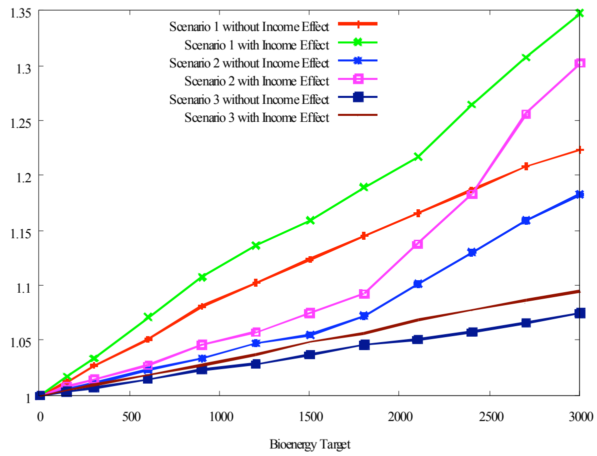

Figure 2 Agricultural expansion

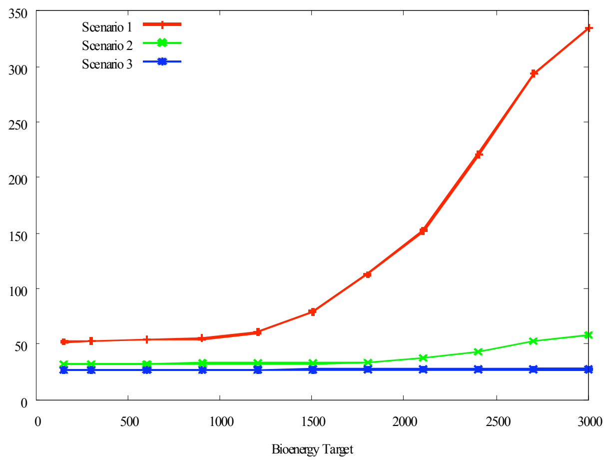

Figure 4 Marginal costs of bioenergy in EU

IV. CONCLUSIONS

This study demonstrates that endogenous income effects can be integrated in partial equilibrium models through an iterative demand shifting procedure. It also shows that these income effects can substantially increase agricultural land and food commodity prices while at the same time undernourishment decreases in some locations. However, such effects are not globally valid and sensitive to policy design. International trade may spill impacts from target to other regions. The proposed method could be implemented in large partial equilibrium models as an intermediate solution until CGE and partial equilibrium model coupling becomes a routine.

V. LIMITATIONS

Several important limitations to this work need to be mentioned. First, the high degree of commodity, resource, technology, and regional aggregation under represents the impact of heterogeneity, adaptation, and substitution in the agricultural sector. Second, the employed model is static and does not consider intertemporal interdependencies. Third, we assume competitive markets and ignore institutional or infrastructure related restrictions. Fourth, we only account for income effects within the agricultural sector but ignore changes in other sectors. Particularly, we ignore the effect of higher energy prices on agricultural production factors. Fifth, we assume a constant coefficient of variation for the calculation of undernourishment prevalence. Sixth, the employed food security indicator considers only the quantity of dietary energy and ignores diet composition constraints. Finally, environmental impacts of bioenergy promotions are not accounted for.

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